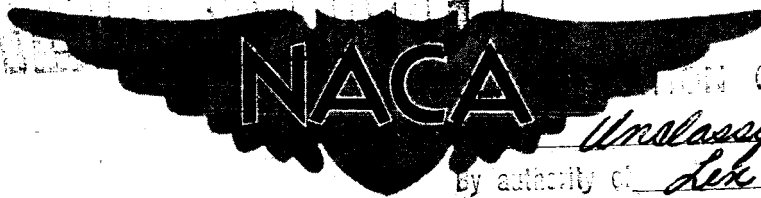


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RESEARCH MEMORANDUM

TURBINE FAILURE INVESTIGATION OF J65-W-4 TURBOJET ENGINE IN AN ALTITUDE TEST CHAMBER

By John E. McAulay, Willis M. Braithwaite, and Carl C. Ciepluch

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Cleveland, Ohio

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REFERENCES AND NOTES

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TURBINE FAILURE INVESTIGATION OF J65-W-4 TURBOJET
ENGINE IN AN ALTITUDE TEST CHAMBER

Abstract

An altitude investigation was conducted to determine the basic mechanism by which J65-W-4 turbine rotor-blade failures were occurring in service. At flight conditions corresponding to high-altitude operation, compressor surge and "hang-up" stall occurred frequently during engine accelerations with the control operable. Surge had no adverse effect on the turbine, but hang-up stall if allowed to persist resulted in failure of the turbine. Similarities between the test failure and those in service were convincing evidence that the mechanism by which the service failures occurred was hang-up stall. The data of this investigation suggested a means of eliminating turbine failures without sacrifices in engine performance.

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RESEARCH MEMORANDUM

TURBINE FAILURE INVESTIGATION OF J65-W-4 TURBOJET

ENGINE IN AN ALTITUDE TEST CHAMBER

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SUMMARY

An altitude investigation was conducted to determine the basic mechanism by which J65-W-4 turbine rotor-blade failures were occurring in service. A J65-W-4 turbojet engine was installed in an altitude test chamber; and a series of controlled engine throttle bursts, with and without inlet-air distortion, were made over a range of altitudes from 25,000 to 45,000 feet, flight Mach numbers from 0.4 to 0.8, and inlet-air temperatures from -40° to 40° F.

At altitudes of 35,000 feet and above and inlet-air temperatures and flight Mach numbers below 40° F and 0.8, respectively, compressor surge and "hang-up" stall occurred frequently during engine accelerations with the control operable. When compressor surge was encountered, no noticeably adverse effect to the turbine resulted. However, when hang-up stall occurred, the engine failed to accelerate and the turbine gas temperatures became excessively high until the engine fuel flow was manually reduced. On the final run, the engine was allowed to remain in the hang-up stall condition, which resulted in turbine blade failure in about $18\frac{1}{2}$ seconds. Similarities between this failure and those in service were convincing evidence that the mechanism by which the service failures occurred was hang-up stall.

Examination of the data obtained during this investigation indicated that the danger of turbine failure could be eliminated without any appreciable sacrifice in engine acceleration time. This could be done by properly altering the fuel acceleration schedule so that the occurrence of hang-up stall was greatly reduced and also by using a temperature override on the control to reduce fuel flow when hang-up stall did occur.

INTRODUCTION

During the period from April through October, 1955, thirteen J65-W-4 turbojet engines operating in FJ-3 airplanes experienced

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failures of the first-stage turbine rotor blades. Of these, five either occurred or were discovered on the ground, while the remaining eight occurred in flight. In general, the first-stage rotor blades were either badly stretched or broken at about midspan, while the other turbine rotor and stator blades suffered somewhat less damage. Metallurgical analysis of the failed blades indicated that they had been exposed to excessively high gas temperatures.

In an effort to discover the cause of the excessive gas temperatures and, consequently, the turbine blade failures, the engine and airframe manufacturers and the Bureau of Aeronautics, Department of the Navy, undertook an intensive experimental investigation on sea-level engine test stands and in flight. During this investigation, a number of possible causes of the turbine blade failures were brought forth:

- (1) Compressor stall with its accompanying high turbine temperatures
- (2) Inadvertent or improper use of the manual or emergency fuel control resulting in overtemperature of the turbine
- (3) Inferior quality of some turbine blades and/or adverse turbine temperature profiles
- (4) Shift of the combustor flame front to the first-stage turbine stators during engine throttle bursts
- (5) Overtemperature of turbine on engine "hot" starts
- (6) Effect of variation of fuels (volatility, position of flame front, chemical content) on turbine life
- (7) Effects of engine installation in airplane, such as inlet-air distortion with accompanying poor turbine temperature profiles and reduced stall margin, and tailpipe loads, which might result in turbine rub
- (8) Fuel-control malfunction

The cause of the turbine failures was not discovered during the ground and flight investigations. It was obvious that an investigation was necessary where altitude conditions could be simulated and the engine could be instrumentated very comprehensively. Consequently, the Bureau of Aeronautics requested the NACA to install a J65-W-4 turbojet engine with its TJL-2 fuel control in an altitude test chamber.

Although the investigation was very exploratory in nature, the objective was, first, to discover and define the conditions that might

lead to failure and, second, to reproduce a failure under closely controlled and adequately instrumentated conditions. Both the engine and airframe manufacturers indicated that a number of engines in service had encountered compressor surge during throttle bursts at altitudes above 30,000 feet. Therefore, it seemed likely that surge was in some way associated with the turbine failures. Thus, the present investigation was directed primarily toward determining the turbine environment during compressor surge.

Steady-state and transient data with the engine control operable were obtained over a range of altitudes from 25,000 to 45,000 feet, flight Mach numbers from 0.4 to 0.8, and inlet-air temperatures from -40 to 40° F. This report presents the typical modes of operation that occurred during controlled engine accelerations and the frequency at which they occurred. It also shows the time history of important engine parameters during an acceleration when the turbine failed. The turbine failure is then compared with one obtained in service. Finally, possible ways of eliminating future turbine failures are discussed.

APPARATUS

Engine and Installation

A photograph of the J65-W-4 turbojet engine installed in the altitude test chamber is shown in figure 1. At static sea-level conditions (NACA standard) and at rated engine speed of 8300 rpm, the engine specifications indicate a thrust level of 7800 pounds at an exhaust-gas temperature of 1184° F.

The compressor consisted of 13 stages and produced a pressure ratio of about 7 and an air flow of about 126 pounds per second at rated sea-level conditions. The combustor was a vaporizing type. The turbine consisted of two stages. The first-stage stator blades were made from Haynes Stellite 31; the first-stage rotor blades from Nimonic 90; and the second-stage stator and rotor blades from Nimonic 80.

During the investigation a standard TJL-2 fuel control was used. Basically, this fuel control scheduled fuel flow as a function of engine speed.

In establishing the effect of inlet-air distortion on the engine performance, the distortion-screen arrangement shown in figure 2 was used. A framework was covered with 4-mesh screen with a wire diameter of 0.047 inch. This screen was primarily used to support another and finer screen of 14-by-16 mesh with a wire diameter of 0.011 inch. This device could be quickly (less than 1 sec) placed in or retracted from the annulus about 17 inches upstream of the inlet guide vanes by a

pneumatic piston-type actuator. The maximum area of the annulus covered by the screen was $1/3$ of the total annulus area and resulted in a 14-percent distortion in total pressure at rated corrected engine speed. Distortion is defined as the difference between the maximum and minimum local total pressure divided by the average total pressure times 100 percent.

Instrumentation

A summary of the steady-state and transient instrumentation is given in table I and figure 3. Only those thermocouples listed in the table on figure 3 were transiently recorded. Steady-state readings were taken of all thermocouples shown on this figure. A hole was cut in the engine skin aft of the turbine so that a motion picture camera could record flame patterns at this station (fig. 1). A periscope was also available in order to observe the turbine outlet and exhaust nozzle from a position directly downstream of the exhaust nozzle.

PROCEDURE

In order to determine the turbine temperature environment during engine accelerations, throttle bursts were made to military throttle setting with the engine control from several initial engine speeds ranging from idle to 95 percent rated engine speed. During these throttle bursts, time histories of the important engine parameters listed in table I were obtained. The following table lists the flight conditions at which throttle bursts were made:

Altitude, ft	Mach number	Inlet temperature, °F
25,000	0.40	-40
35,000	.80	-40
^{a,b} 35,000	.54	-40
^b 35,000	.54	0
^{a,b} 35,000	.54	40
40,000	.61	-40
45,000	.68	-40

^aInlet-air distortion.

^bWave off.

As indicated in the table, engine accelerations were also made at some flight conditions with inlet flow distortion or with wave-off-type throttle manipulations. Wave-off-type throttle manipulations consisted of stabilizing the engine at military speed, then quickly moving the throttle to its idle position, and, finally, rapidly moving the throttle

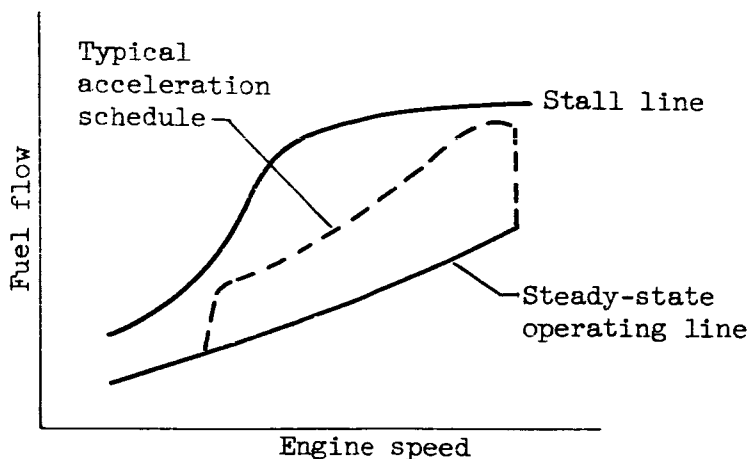
back to its military position before the engine stabilized at idle. In some cases several cycles of this type of throttle movement were tried.

RESULTS AND DISCUSSION

Response of Engine to Throttle Bursts

Time histories of typical throttle bursts. - Throttle bursts made with the engine control in operation and undistorted inlet flow disclosed three modes of compressor response. These three modes of compressor response are shown in figures 4 to 6, which present typical oscillograph traces of several engine parameters. The recorded engine parameters, which increase in the direction of the arrow on each trace, are engine speed, fuel flow, compressor-inlet total pressure, compressor-discharge total pressure, local turbine-discharge gas temperature, and throttle position.

Figure 4 shows the engine behavior during a normal acceleration. The throttle was moved rapidly from its part-speed to military rated position. This throttle movement resulted in the fuel control metering fuel flow according to the preset acceleration schedule as qualitatively illustrated below:



Basically, this schedule called for a step in fuel flow from the steady-state operating line toward the compressor stall line; then a ramp increase in fuel flow; and, finally, as rated engine speed is approached, a reduction in fuel flow to the rated steady-state value. Increasing fuel flow from the initial value raised the turbine temperature level and, consequently, the engine speed. This rise in the turbine temperature level and engine speed produced an increase in the

compressor-discharge pressure, which was smooth and continuous for the acceleration shown in figure 4. The maximum indicated turbine-discharge gas temperature obtained during this acceleration was about 1450° F.

The second of the compressor modes of response is presented in figure 5, which portrays an acceleration during which compressor surge occurred. The surge was characterized by one or more cycles of compressor stall and recovery. This acceleration was similar to that shown in the previous figure until, as indicated by the trace of compressor-discharge pressure, the compressor repeatedly stalled and recovered (surged). The surge reduced to some extent the engine acceleration; but, because of its short duration (about 1.6 sec), the turbine blade temperatures did not become excessive. Compressor surge, such as that shown in figure 5, is typical of turbojet engines when the acceleration schedule intersects the compressor stall line at high corrected engine speeds.

The third mode of compressor response is presented in figure 6, which shows the results of an acceleration during which complete or "hang-up" stall occurred. Complete or hang-up stall is a condition where the compressor stalls and does not recover. This acceleration proceeded in a manner similar to that shown in figure 4 until there occurred a discontinuous decrease in the compressor-discharge pressure. In this case, the compressor did not recover from stall as it did during the acceleration depicted in figure 5. Instead, it remained in the completely stalled condition until fuel flow was substantially reduced by manual throttle movement. Also, the engine acceleration was drastically reduced during hang-up stall and in many cases the engine actually began to decelerate almost immediately. The inability of the engine to accelerate resulted in the engine fuel control maintaining the high acceleration fuel flow, inasmuch as the top-speed governor of the control did not become effective. Thus, the engine control tended to keep the compressor in complete stall.

The characteristics of hang-up stall and the engine control were such that, when stall occurred, and, consequently, the air flow was reduced, the engine fuel-air ratio increased from about 0.025 to about 0.050. This increase in fuel-air ratio resulted in turbine gas temperatures considerably above 2000° F. Hang-up stall, then, appeared to be a likely mechanism by which turbine failure might occur as long as the engine throttle (fuel flow) was allowed to remain at the position at which stall occurred. As a result, until sufficient data were obtained to map out the conditions under which surge and hang-up stall occurred, the engine fuel flow was manually reduced whenever hang-up stall was encountered so as to unstall the compressor and thereby avoid overheating the turbine.

This type of complete or hang-up stall at high corrected engine speeds (about 105 percent of rated) was an engine behavior unlike anything previously observed at this laboratory with full-scale engines. However, complete stall has been obtained on full-scale engines in regions of lower corrected engine speed and on compressors tested as components at both low and high corrected speeds. A basic discussion of the various types of stall and the factors that influence these types is reported in reference 1.

Conditions under which surge and complete stall occurred. - The following sets of tables are presented in order to indicate the conditions under which compressor surge and hang-up stall occurred. Because surge and stall did not always occur when a throttle burst was made at a given set of conditions, a statistical approach is used in summarizing the results. In some cases hang-up stall was preceded by surge. The first of these tables gives the results obtained at various inlet pressures and temperatures with uniform flow existing at the compressor inlet:

Altitude, ft	Flight Mach number	Inlet-air temperature, °F	Number of bursts	Percent of total		
				Surge	Hang-up stall	Surge and stall free
25,000	0.40	-40	6	0	0	100
35,000	.80	↓	3	0	0	100
↓	.54	↓	22	36	46	18
↓	↓	0	10	30	0	70
↓	↓	40	7	0	0	100
40,000	.61	-40	6	0	67	33
45,000	.68	-40	19	0	53	47

The data given in the preceding table indicate that compressor surge and stall with undistorted inlet-air flow occurred only at engine-inlet pressure levels below that present at an altitude of 35,000 feet and a flight Mach number of 0.80. Even at low inlet pressures, the frequency at which surge or stall occurred could be markedly reduced by increasing the inlet-air temperature. For example, increasing the inlet-air temperature from -40° to 40° F at an altitude of 35,000 feet and a Mach number of 0.54 reduced the occurrence of surge or stall from 82 to 0 percent. The explanation of these trends can be found by considering the characteristics of the fuel control schedule and the effect of inlet pressure and corrected engine speed (inlet temperature) on the compressor stall margin. The fuel control basically scheduled fuel flow as a function of mechanical engine speed. The control did not account for the reduction in compressor stall margin with decreased inlet pressure (Reynolds number) or with increased corrected engine speed, which are illustrated in reference 2.

Data in the preceding table, along with results obtained by the manufacturer on the sea-level test stand and the NACA in another investigation, indicate that, if the acceleration schedule intersects the stall line, surge would result at low altitudes, while hang-up stall would become more prevalent at high altitudes.

Inasmuch as a uniform inlet-air-flow distribution is seldom, if ever, obtained in flight, the effect of inlet-air distortion on the nature of the compressor response to fuel bursts was investigated. Therefore, a method of creating an inlet-air distortion was used to obtain a circumferential distortion of 14 percent (see the section APPARATUS). A typical engine throttle burst at an altitude of 35,000 feet, a Mach number of 0.54, and an inlet-air temperature of -42°F with this inlet pressure distortion is presented in figure 7. During this acceleration, complete compressor stall occurred. The effect that this inlet-air distortion had on the occurrence of surge and stall is presented in the following table:

Inlet-air distortion, percent	Altitude, ft	Flight Mach number	Inlet-air temperature, $^{\circ}\text{F}$	Number of bursts	Percent of total		
					Surge	Hang-up stall	Surge and stall free
14	35,000	0.54	-40	4	0	100	0
14	↓	↓	40	6	66	34	0
0			-40	22	36	46	18
0	↓	↓	40	7	0	0	100

The data presented in this table show that a 14-percent circumferential distortion greatly increased the occurrence of compressor surge and stall. This trend is expected inasmuch as distortion has the effect of reducing the compressor stall margin (ref. 2). Because the control fuel schedule remained the same for both the distorted and uniform inlet-air-flow cases, accelerations using the engine control and with inlet-air distortion encountered surge or stall at lower corrected engine speeds than those with uniform inlet-air flow. This difference is illustrated by comparing the surge or stall points of figures 5 and 7.

Throttle manipulation which simulates a wave-off-type maneuver, that is, a throttle chop followed quickly by a throttle burst, is also of interest. In figure 8 are presented typical examples of wave-off-type throttle bursts during which surge (fig. 8(a)) and surge and stall

(fig. 8(b)) occurred. The effect of this type of throttle movement on the occurrence of surge and stall is summarized in the following table:

Type of burst	Altitude, ft	Flight Mach number	Inlet-air temperature, °F	Number of bursts	Percent of total		
					Surge	Hang-up stall	Surge and stall free
Wave off	35,000	0.54	-40	4	0	100	0
↓	↓	↓	0	3	67	33	0
↓	↓	↓	40	2	100	0	0
Normal	↓	↓	-40	22	36	46	18
↓	↓	↓	0	10	30	0	70
↓	↓	↓	40	7	0	0	100

Examination of the data shown in this table and in figure 8 indicates that the results were similar to those obtained with inlet-air distortion, namely, an increase in the occurrence of surge and stall and a reduction in the corrected engine speed at which surge and stall occurred. Comparison of a number of wave-off and single throttle bursts indicated, first, that the fuel schedules for the two types of throttle bursts were the same and, second, that the compressor stall pressure ratio and, consequently, the stall fuel flow were sizably reduced during the wave-off-type throttle bursts. The reason for this reduction is not clear.

In summarizing, it was established that, when engine throttle bursts with the control were made at certain flight conditions, one of three things happened. Either the engine accelerated normally, compressor surge occurred, or hang-up stall was encountered. Hang-up or complete compressor stall seemed to be a condition almost certain to result in turbine failure if allowed to persist.

Turbine Failure

Description of turbine-failure throttle burst. - Since a phenomenon had been found that might result in turbine failure and the conditions had been determined at which it occurred, it was necessary to demonstrate that this phenomenon would cause turbine failure and that this failure was typical of those in service. Consequently, at an altitude of 35,000 feet, a flight Mach number of 0.54, and an inlet-air temperature of -40° F, a throttle burst was made from about 85 percent rated mechanical engine speed. Once the throttle had been moved to the full military position, it was held in a fixed position after the stall occurred. The time history of important engine parameters during this throttle burst is presented in figure 9. The engine acceleration proceeded in a normal fashion for approximately $2\frac{3}{4}$ seconds when 1 cycle of

compressor surge occurred at about 97 percent of rated engine speed. By the time the compressor recovered, the engine had accelerated to about 98 percent of rated engine speed and the top-speed governor of the fuel control began to reduce fuel flow. However, at 99 percent speed the compressor stalled and did not recover. Because the engine started to decelerate after stall had occurred, the fuel control increased the fuel flow back up to the previous high level along the engine acceleration schedule. As previously stated, the engine fuel-air ratio reached a value of about 0.05 during complete stall. The turbine-discharge gas temperature, as indicated in figure 9, peaked at about 2300° F. The turbine-inlet temperature was considerably above 2300° F. After approximately $18\frac{1}{2}$ seconds from the initiation of the throttle burst, the turbine failed.

The temperature levels through the turbine during this transient are presented in figure 10. All the lines representing temperatures were obtained from a transient record other than that shown on figure 9 but obtained concurrently with it. The actual measured values of temperature are recorded in figure 10. However, it was estimated that during stall the turbine-inlet and interstage gas temperatures, primarily because of radiation errors, read about 600° and 300° F too low, respectively. Thus, these data indicated that local turbine-inlet gas temperatures rose to about 3200° F shortly after the compressor encountered stall. The lag of the metal temperatures as compared with the gas temperatures is associated with the blade time constants.

Appearance of failed turbine. - The photographs of the first-stage turbine stator, shown in figures 11(a) and (b), indicate that damage to these blades is confined to the trailing edges, where a number of blades suffered minor projectile damage. A portion of the first-stage rotor-blade row is shown in figure 11(c). This photograph clearly shows that these blades stretched and cracked, particularly at mid-span, before the blade tips separated from the rest of the blade.

The second-stage rotor and stator, which are shown in figures 11(d) and (e), respectively, show a large amount of metal deposited on the blades. Also, the tips of the second-stage rotor blades are rounded off, undoubtedly a result of the metal from the first-stage blades coming in contact with the second-stage blades.

Comparison of service and test failures. - Photographs of typical turbine blades from a service failure and a test failure are presented in figure 12. Shown on the figure from left to right are a first-stage stator, a second-stage rotor, and three first-stage rotor blades. The similarities between the two sets of blades are quite striking, even to the location of metal deposits on the leading edge of the second-stage rotor blades. Representatives of both the engine and airframe

manufacturers accepted these similarities as proof that hang-up compressor stall is the mechanism by which the service failures occurred.

Turbine-failure analysis. - A metallurgical analysis of the failed blades and the metal deposited downstream of the first-stage rotor indicated that the first-stage stator- and rotor-blade temperatures at the time of failure were about 2150° and 2300° F, respectively. The analysis also indicated that the first-stage rotor-blade failure occurred when the metal temperature was sufficiently high to weaken the blades in the grain boundaries. This weakening of the blades in conjunction with the blade stress resulted in failure.

Blade temperature analysis. - The data presented in figure 13 show the variation of measured and calculated turbine-inlet gas temperature, measured and calculated stator-blade temperature, and calculated rotor-blade temperature with time as measured from the initiation of the failure throttle burst of figure 10. The measured turbine-inlet gas temperature shown on this figure is the same as that presented in figure 11, except that it has been corrected for radiation effects. The calculated blade temperatures were obtained by approximating the blade heat-transfer coefficient and time constant, where the time constant is a function of the heat-transfer coefficient and the blade material and geometry. Also shown on the figure are the metal temperatures of the first-stage stator and rotor blades as estimated from the metallurgical analysis discussed in the previous paragraph.

All three methods of obtaining the blade temperature of the first-stage stator at the point of turbine failure show reasonably close agreement. The highest value of 2150° F and the lowest value of 2000° F were obtained by a metallurgical analysis and thermocouple measurement, respectively. The first-stage rotor-blade temperature obtained by calculation and metallurgical analysis agreed almost exactly at about 2300° F. The rotor-blade temperature was higher than the stator-blade temperature at the point of failure because of the lower time constant of the rotor blade.

Methods to Alleviate or Eliminate the

Possibility of Turbine Failures

Although several methods could be utilized to alleviate the possibility of turbine failure, only one provides a positive means of eliminating turbine failures. This method requires the use of a turbine-outlet temperature or compressor-outlet pressure signal to determine the presence of compressor surge or hang-up stall. Such a signal could then produce a sufficient reduction in fuel flow to permit the compressor to recover from stall. Inasmuch as extended overtemperature of the turbine is the immediate cause of the failures, it is desirable that

the sensing signal would originate from a thermocouple, preferably one at the turbine outlet. Such a system was evaluated and proved quite successful (ref. 3).

As was pointed out previously, hang-up stall occurred at high-altitude, low-inlet-temperature conditions on about 50 to 60 percent of the controlled engine throttle bursts with uniform inlet-air-flow profiles. Thus, even with the limiting temperature addition to the engine control, practical considerations undoubtedly make it necessary to greatly reduce the frequency of hang-up stall occurrence. This can be done by altering the fuel acceleration schedule, which is shown in figure 14 on coordinates of fuel flow and engine speed for an altitude of 35,000 feet, flight Mach number of 0.54, and inlet-air temperature of -40° F. Also presented on this figure are the steady-state operating line and the stall line. Reducing the fuel acceleration schedule at high engine speeds is necessary so that hang-up stall is only likely to occur under severe conditions, that is, high inlet-air-flow distortion and wave-off-type throttle bursts. The loss in acceleration time by reducing the acceleration schedule at high engine speeds could be partly or wholly regained by enriching the schedule in the medium-speed range (fig. 14). Thus, by so shifting the acceleration schedule, it is possible to greatly reduce the occurrence of hang-up stall. Furthermore, the addition of a pressure- or temperature-sensing element to the control would avoid engine damage whenever hang-up stall did occur.

The likelihood of encountering hang-up stall and, consequently, engine failure can be further reduced by increasing the compressor stall margin. This increased stall margin could be obtained by increased turbine stator or exhaust-nozzle area and, possibly, by minor modifications to compressor geometry. Unfortunately, the probable gains from such changes are small and generally are accompanied by losses in engine performance.

CONCLUDING REMARKS

From an investigation of the J65-W-4 turbojet engine, it was found that turbine failures encountered in service were caused by compressor hang-up stall, which is accompanied by excessively high turbine temperatures. At altitudes of 35,000 feet and above, and at inlet-air temperatures and flight Mach numbers below 40° F and 0.8, respectively, compressor surge and hang-up stall frequently occurred during engine accelerations with the control operable. When surge alone was encountered, the engine was able to accelerate and reach a normal operating condition in a time comparable with surge-free operation. However, when hang-up stall occurred, the turbine gas temperatures became excessively high and the engine was unable to accelerate. Also, the

4109 engine remained in the stalled condition until the engine fuel flow was substantially reduced by manual throttle movement. The investigation was climaxed by allowing the engine to continue operating in the hang-up stall condition encountered during a throttle-burst acceleration with the standard engine control. The result was a turbine failure about $18\frac{1}{2}$ seconds after the throttle burst was made. Similarities between this failure and those in service were convincing evidence that the mechanism by which the service failures occurred was hang-up stall.

Examination of the characteristics of the engine acceleration schedule and stall margin along with those of hang-up stall suggested that the danger of turbine failure could be eliminated by control modifications without any appreciable sacrifice in engine acceleration time. The likelihood of encountering hang-up stall could be substantially reduced by altering the fuel acceleration schedule so that it more closely approximated the shape of the stall line. In addition, the use of an exhaust-gas temperature signal to the control would permit sufficient fuel flow reduction to allow the compressor to recover, even on occasions when hang-up stall occurred.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 16, 1956

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2. Fenn, David B., and Sivo, Joseph N.: Effect of Inlet Flow Distortion on Compressor Stall and Acceleration Characteristics of a J65-B-3 Turbojet Engine. NACA RM E55F20, 1955.
3. Stiglic, Paul M., and Heppler, Herbert J.: Experimental Investigation of an Overriding Control to Effect Recovery from Surge and Stall in a Turbojet Engine. NACA RM E56H08, 1956.

TABLE I. - INSTRUMENTATION

Measured parameter	Steady-state instrumentation		Transient instrumentation		
	Type of probe	Recording method	Measuring device	Recording method	Approx. time constant (for 35,000 ft), sec
Engine speed	-----	Electronic tachometer	Electronic tachometer	Brush recorder	0.10
Throttle position	-----	Gauge	Potentiometer	Brush recorder	-----
Fuel flow	-----	Rotameter	Potter flow meter	Brush recorder	-----
Compressor-inlet total pressure	Total-head tube	Manometers	Aneroid-type pressure sensor with strain-gage element	Brush recorder	0.05
Compressor-outlet total pressure	Total-head tube	Manometers	Aneroid-type pressure sensor with strain-gage element	Brush recorder	0.05
Turbine-inlet gas temperature	Unshielded thermocouple	Flight recorder	Unshielded thermocouple	Consolidated recorder	0.60
Turbine metal temperature	Imbedded thermocouple	Flight recorder	Imbedded thermocouple	Consolidated recorder	0.60
Turbine-outlet temperature	Shielded thermocouple	Flight recorder	Shielded thermocouple	Brush and consolidated recorders	0.60

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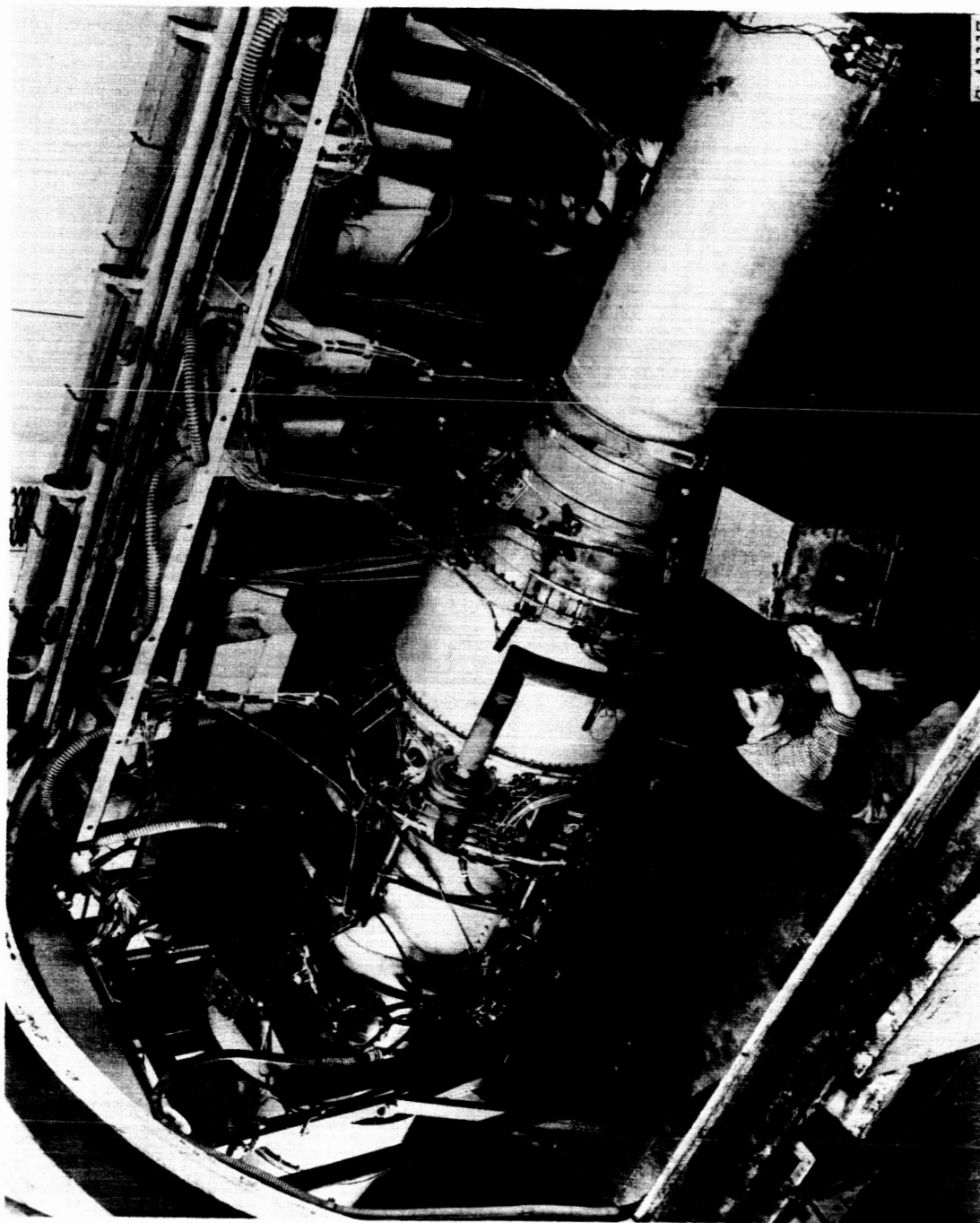


Figure 1. - Installation of J65-W-4 turbojet engine in altitude test chamber.

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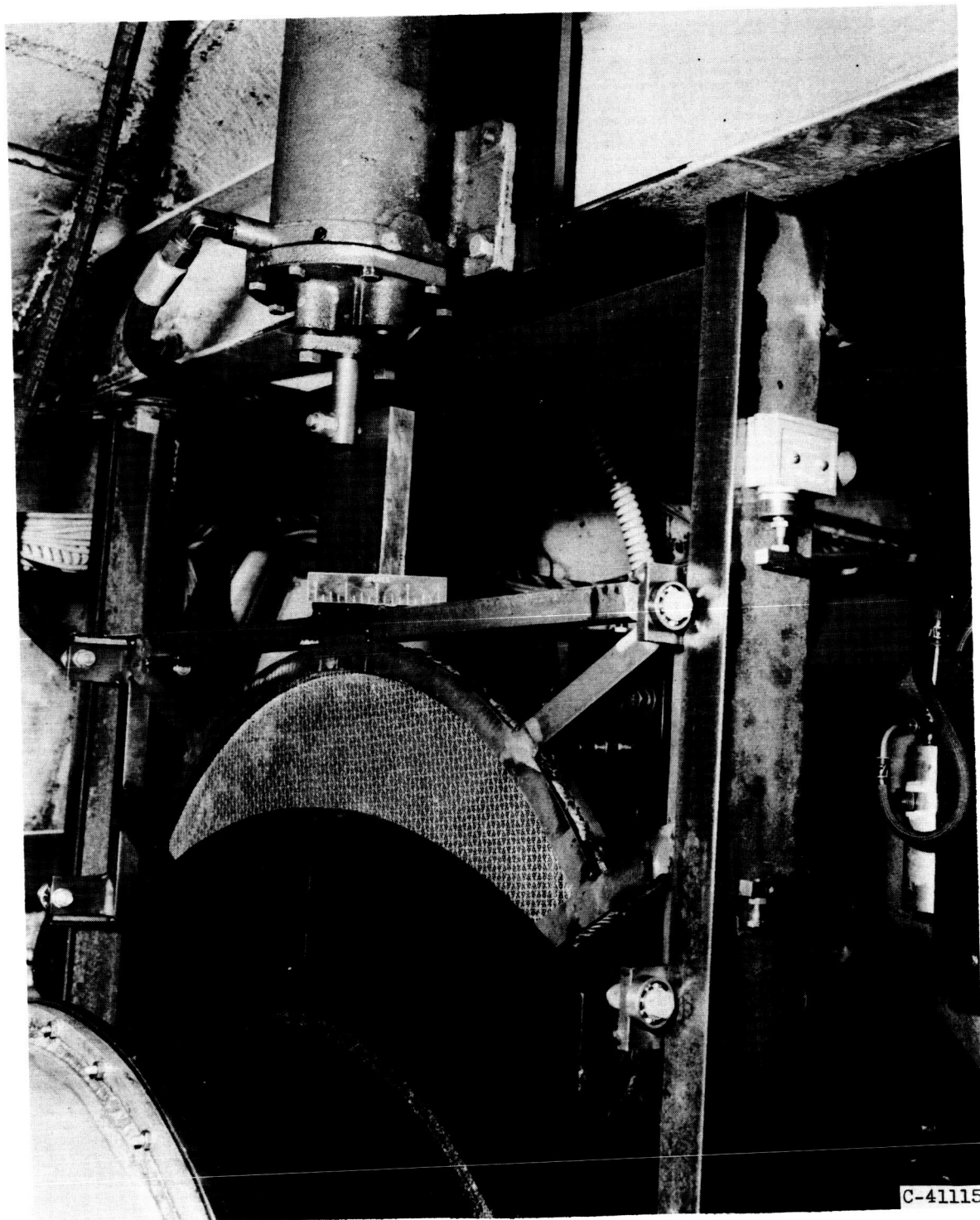


Figure 2. - Inlet-air distortion-screen mechanism.

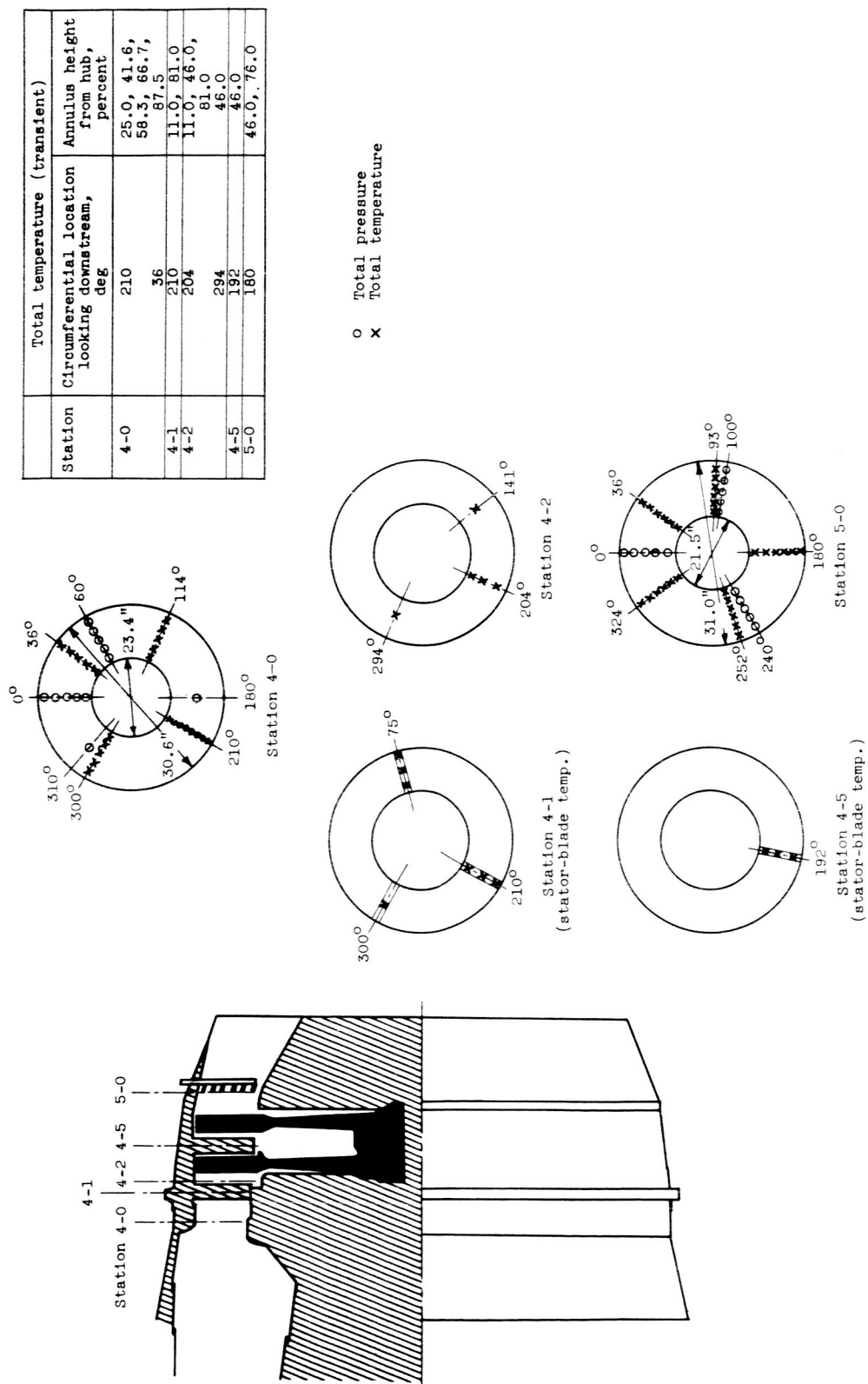


Figure 3. - Turbine instrumentation stations for J65-W-4-turbojet engine. (All station cross sections looking downstream.)

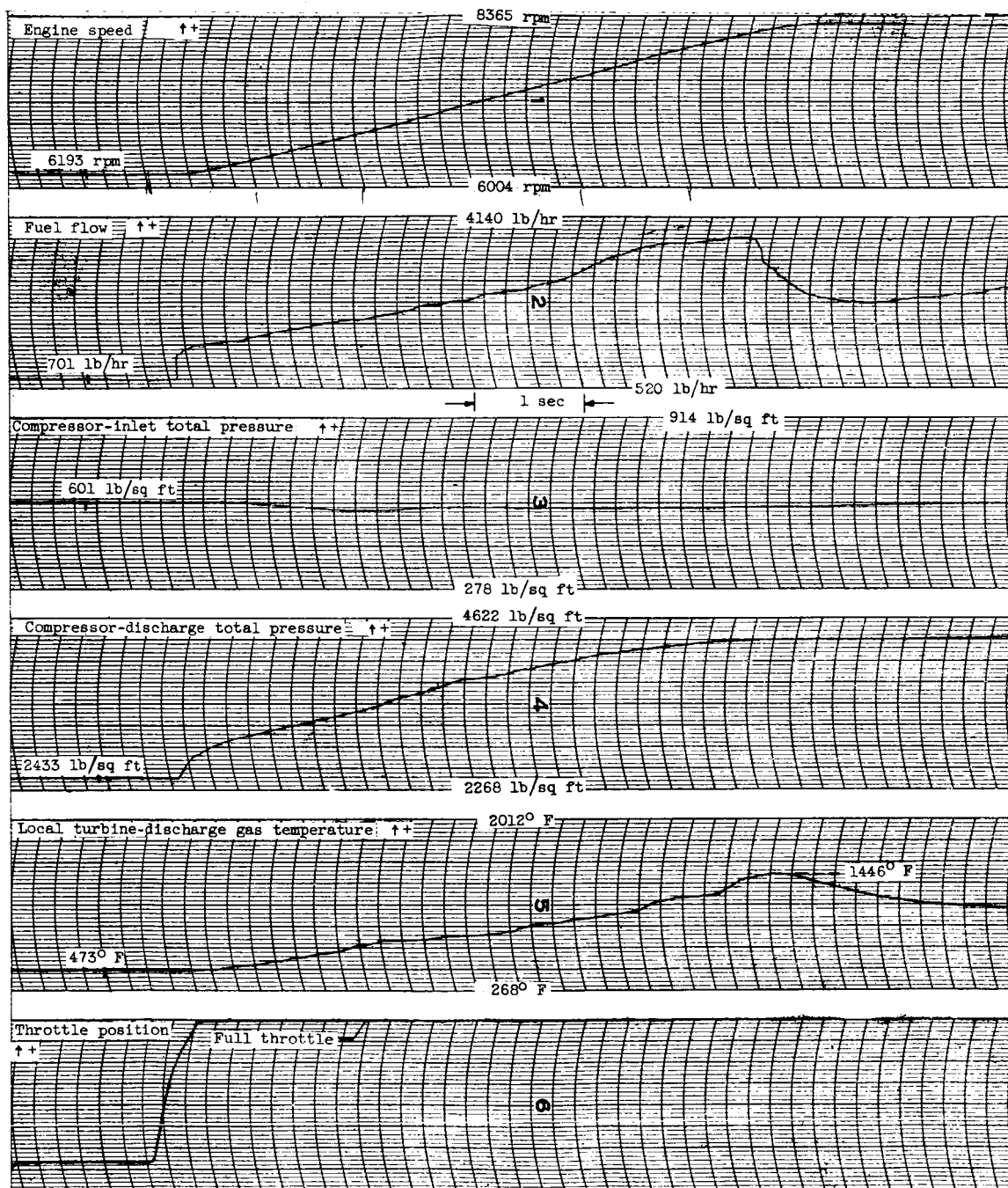


Figure 4. - Typical oscillogram of engine variables during engine acceleration without surge or stall. Altitude, 35,000 feet; flight Mach number, 0.54; inlet-air temperature, -40° F.

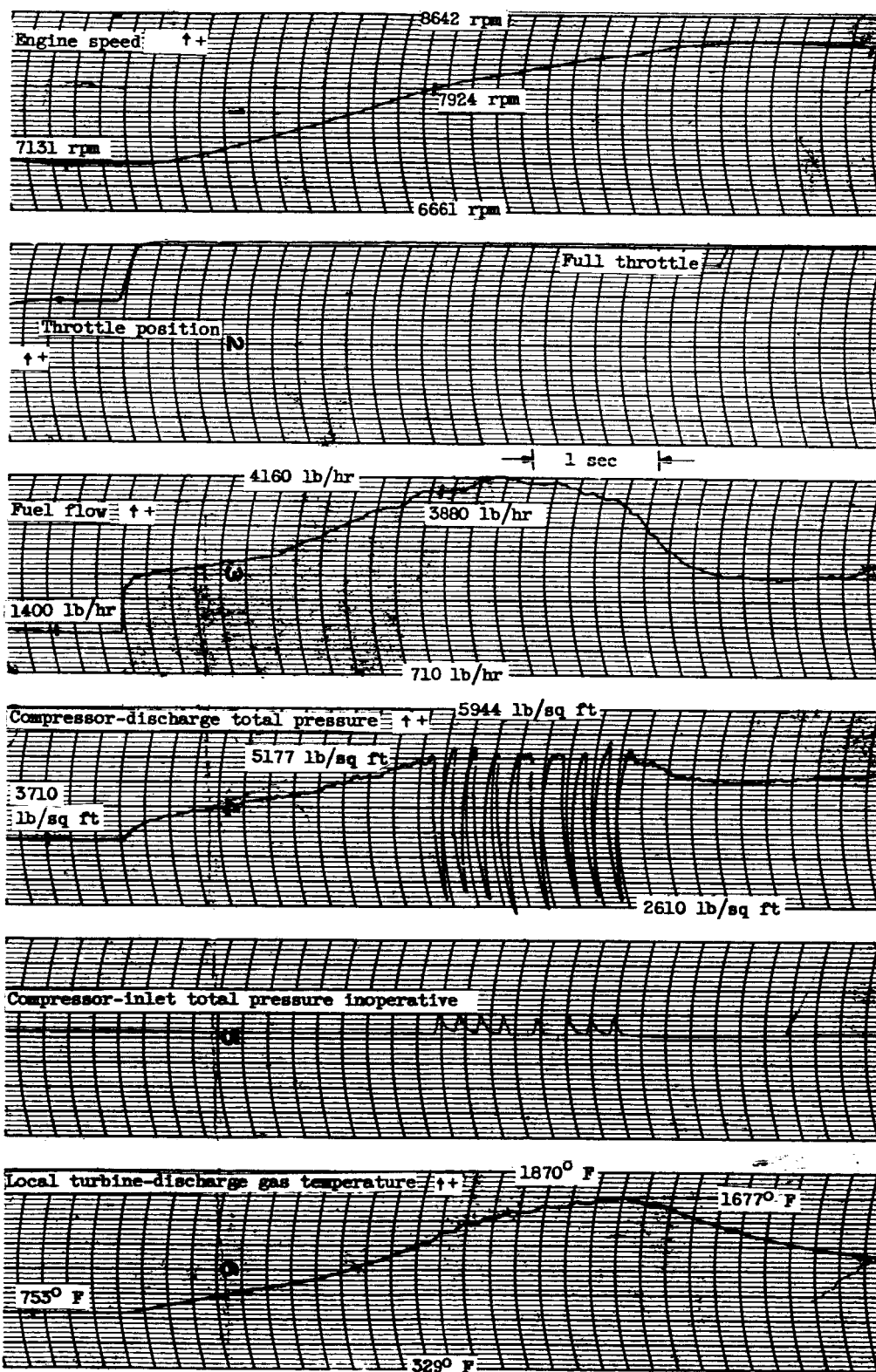


Figure 5. - Typical oscillogram of engine variables during engine acceleration with surge. Altitude, 35,000 feet; flight Mach number, 0.54; inlet-air temperature, -40° F.

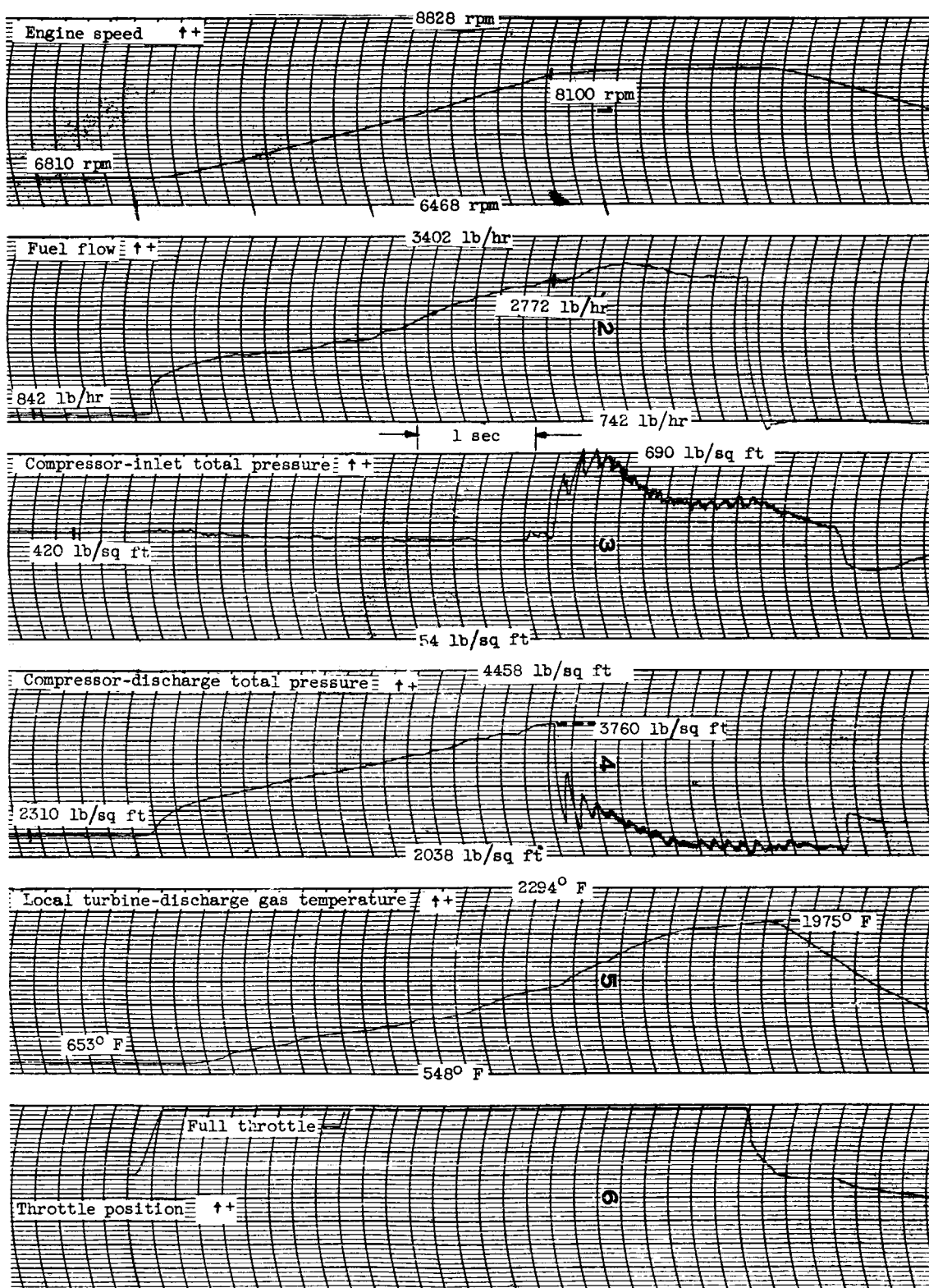


Figure 6. - Typical oscillogram of engine variables during engine acceleration with "hang-up" stall. Altitude, 45,000 feet; flight Mach number, 0.68; inlet-air temperature, -40° F.

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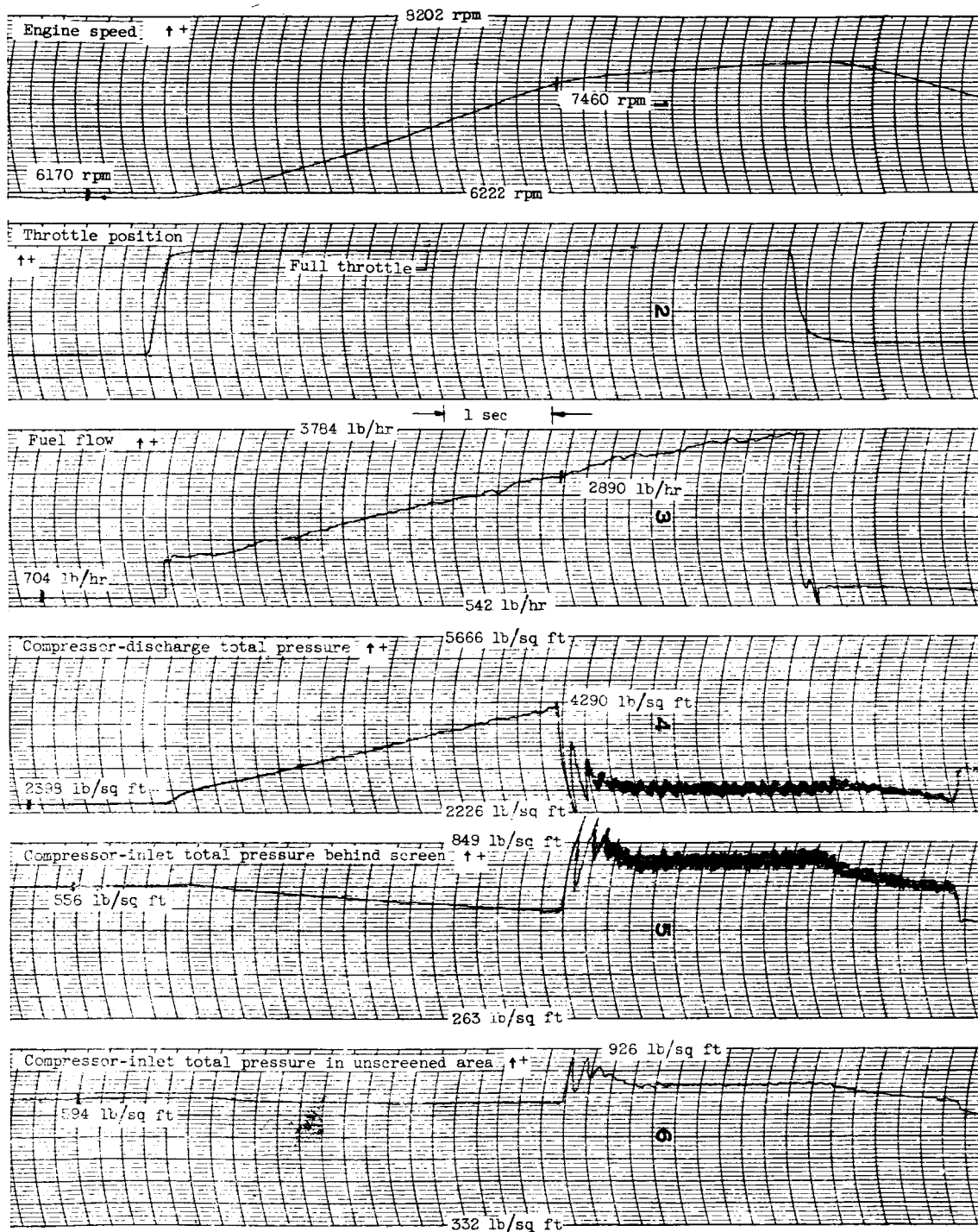


Figure 7. - Typical oscillogram of engine variables during engine acceleration with "hang-up" stall and inlet-air-flow distortion. Altitude, 35,000 feet; flight Mach number, 0.54; inlet-air temperature, -42° F.

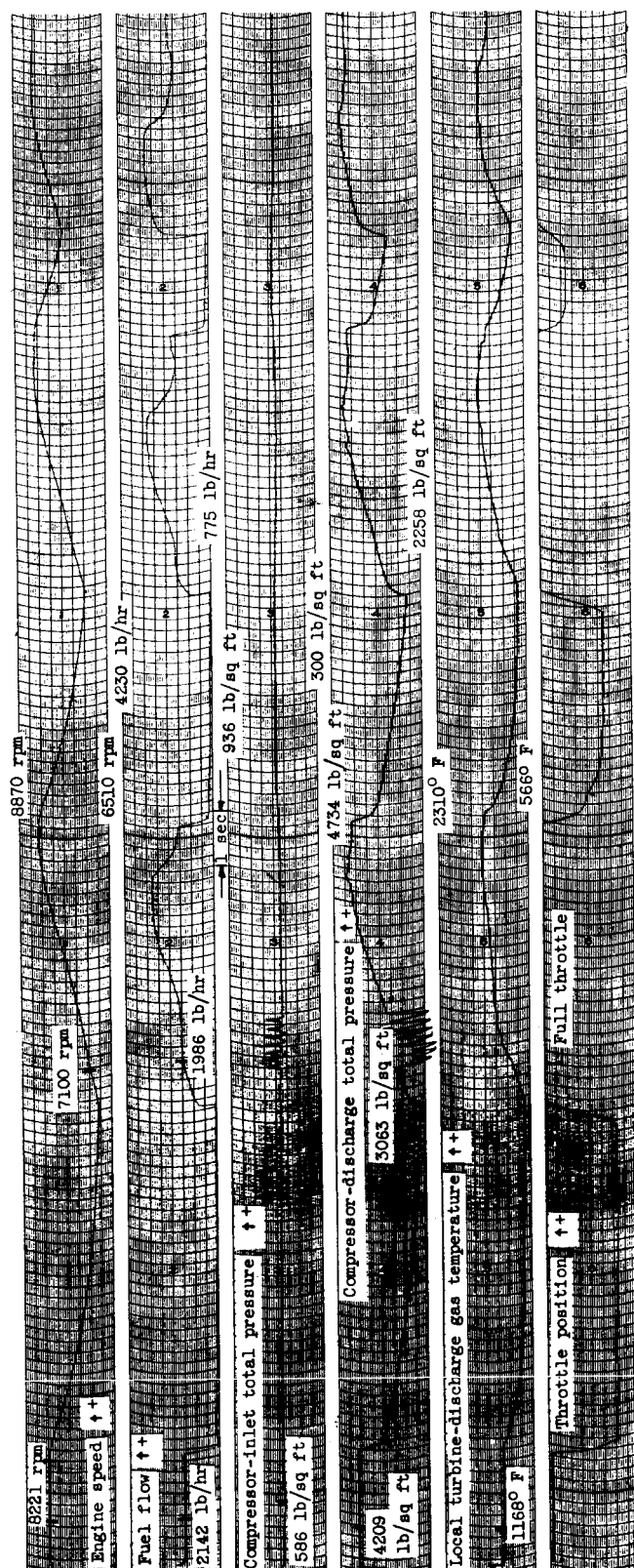
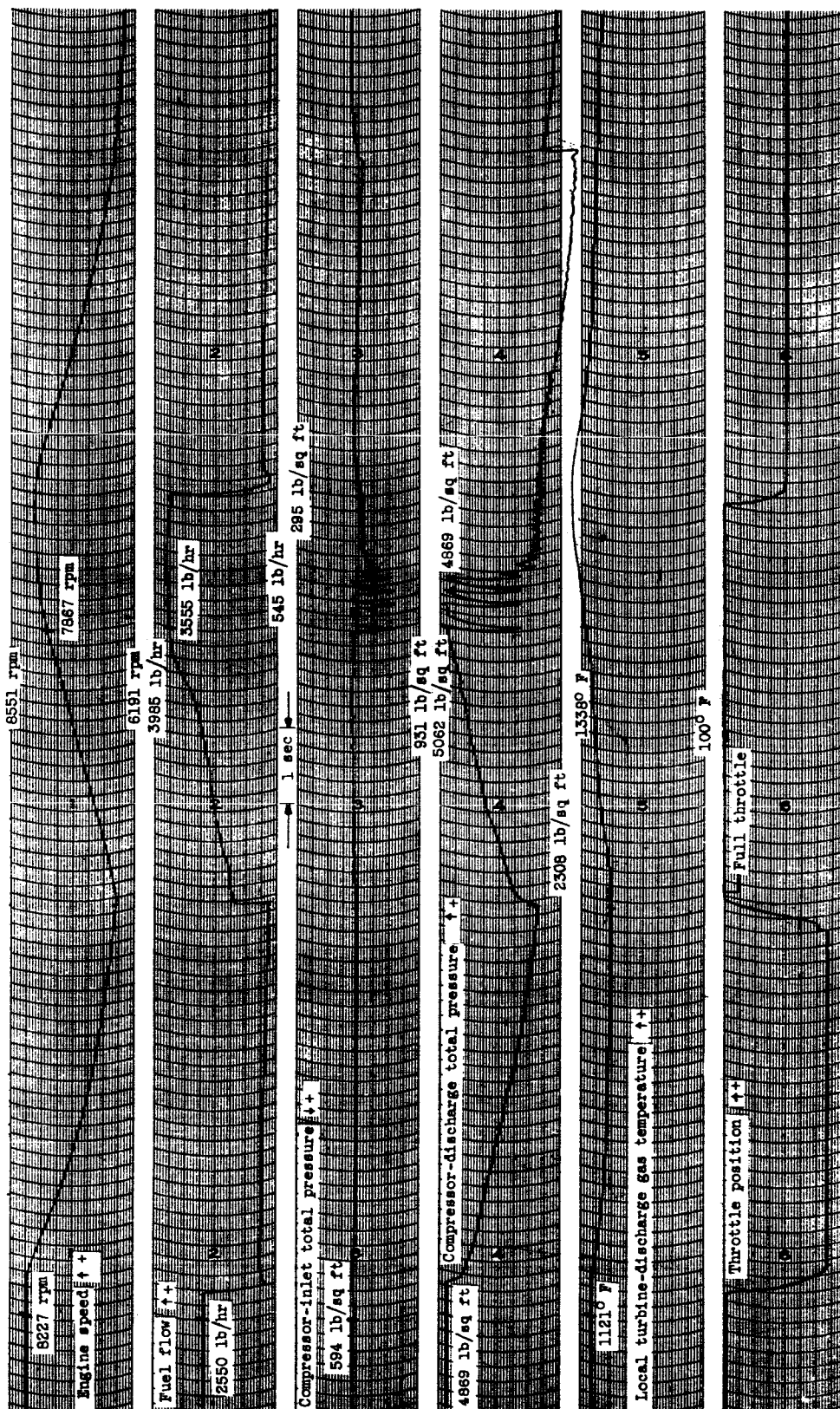


Figure 8. - Wave-off throttle bursts. Altitude, 35,000 feet; flight Mach number, 0.54.

(a) Inlet-air temperature, 40° F.



(b) Inlet-air temperature, -45° F.
 Figure 8. - Concluded. Wave-off throttle bursts. Altitude, 35,000 feet; flight Mach number, 0.54.

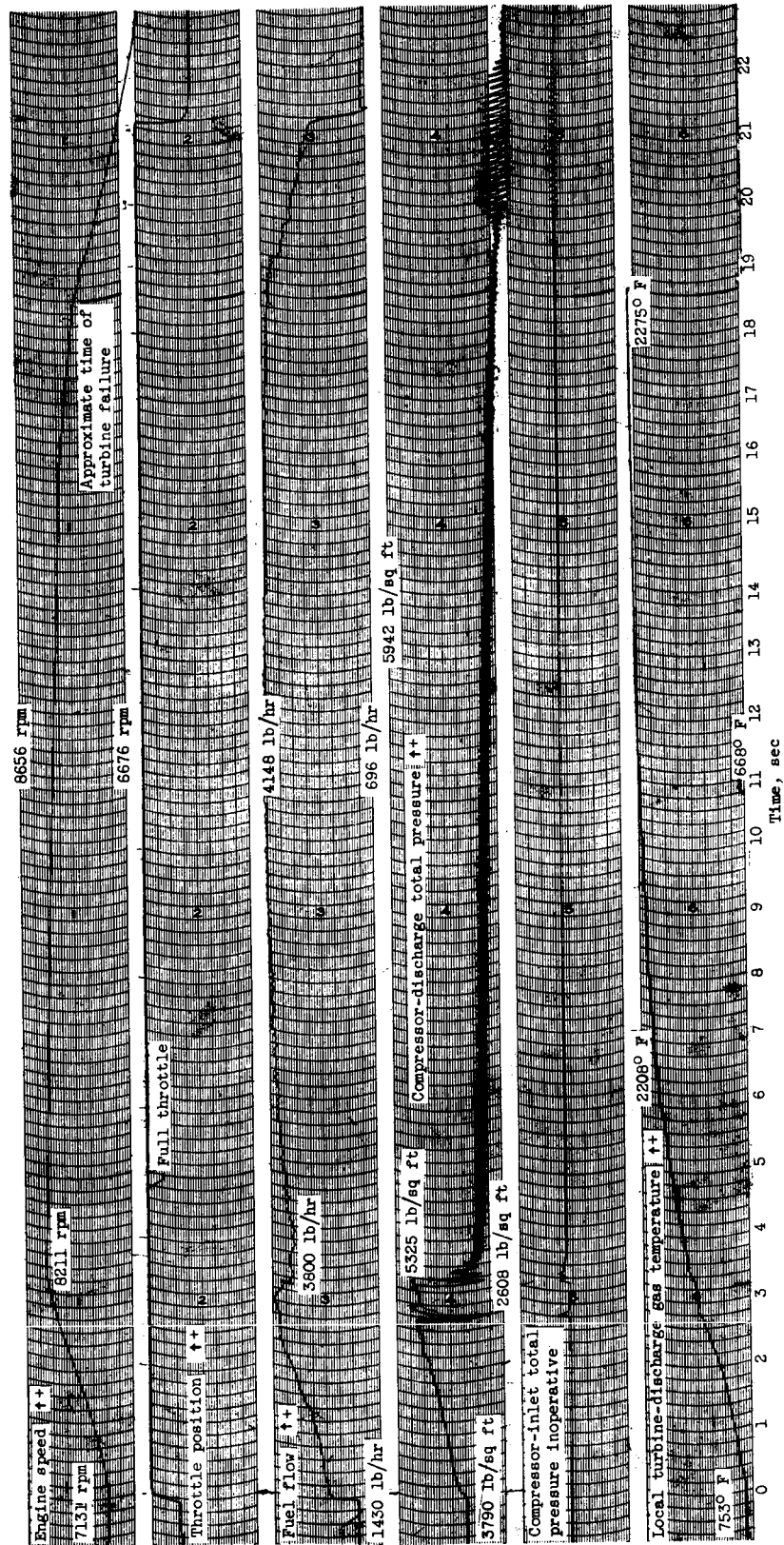


Figure 9. - Oscillogram of engine acceleration encountering surge and stall and resulting in turbine failure. Altitude, 35,000 feet; Mach number, 0.54; inlet-air temperature, -40° F.

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CL-4

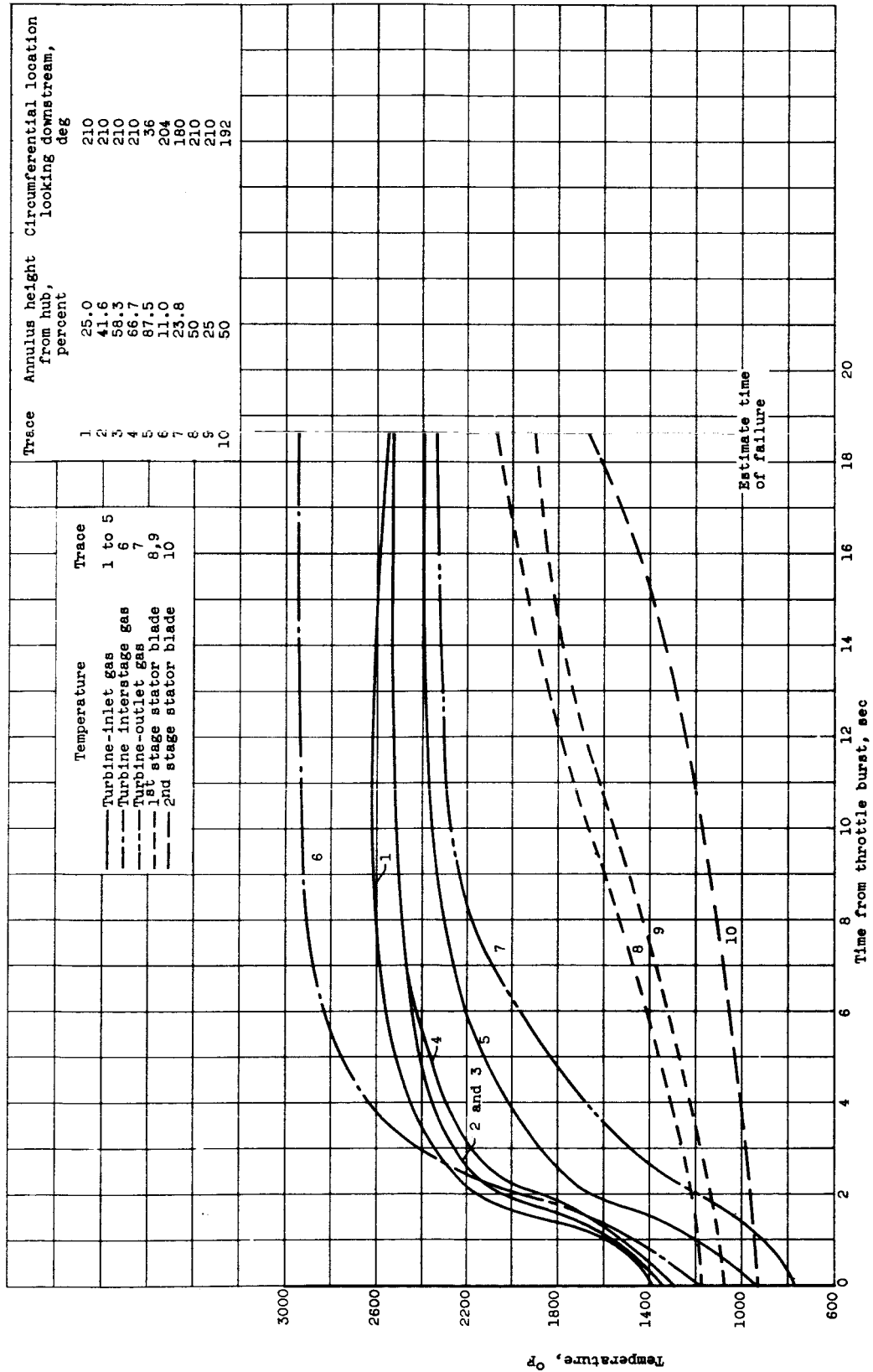
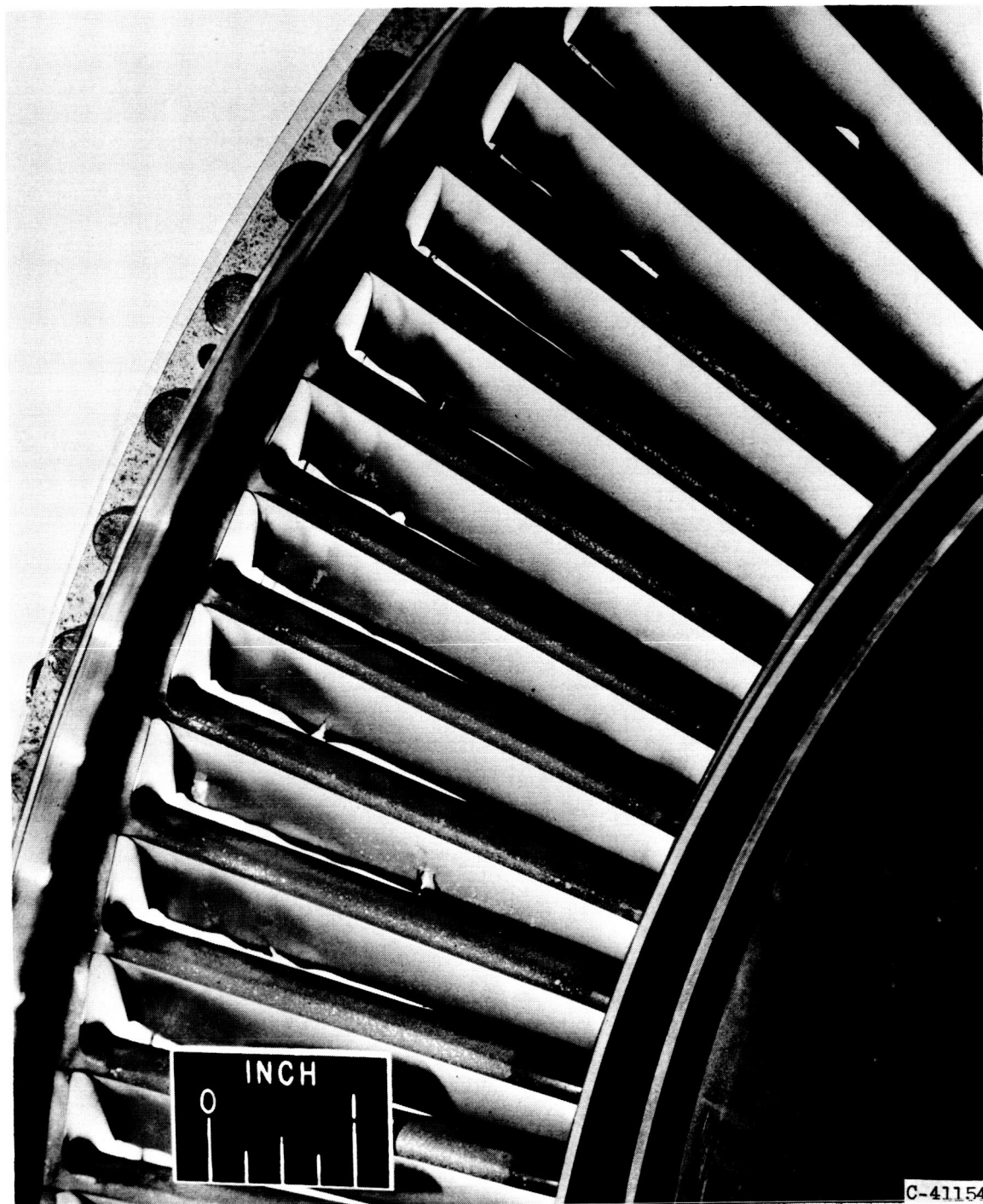


Figure 10. - Time history of turbine temperatures during failure run. Altitude, 35,000 feet; flight Mach number, 0.54; inlet-air temperature, -400 F.

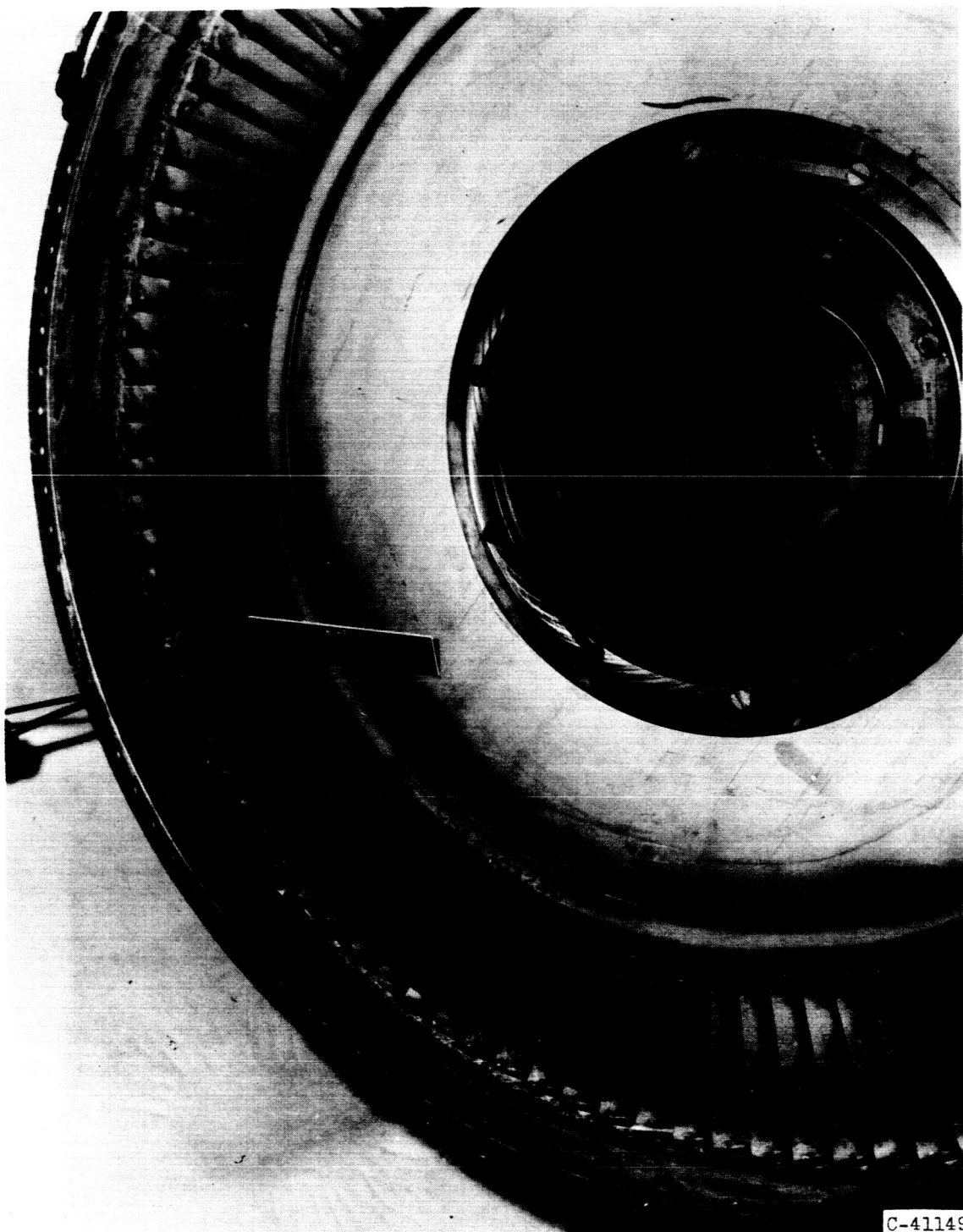


(a) Leading edge of first-stage stator.

Figure 11. - Damaged turbine blades.

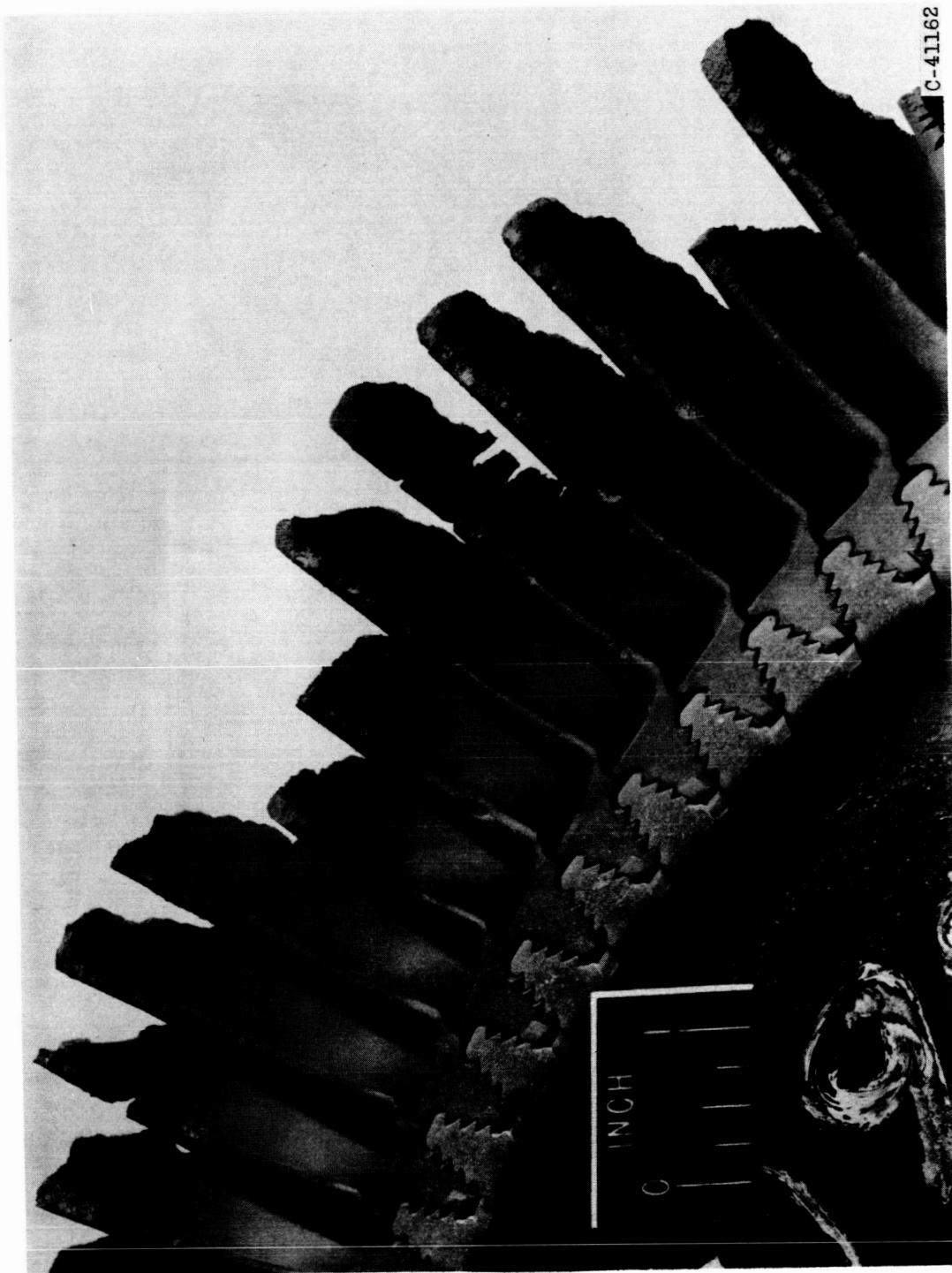
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CL-4 back



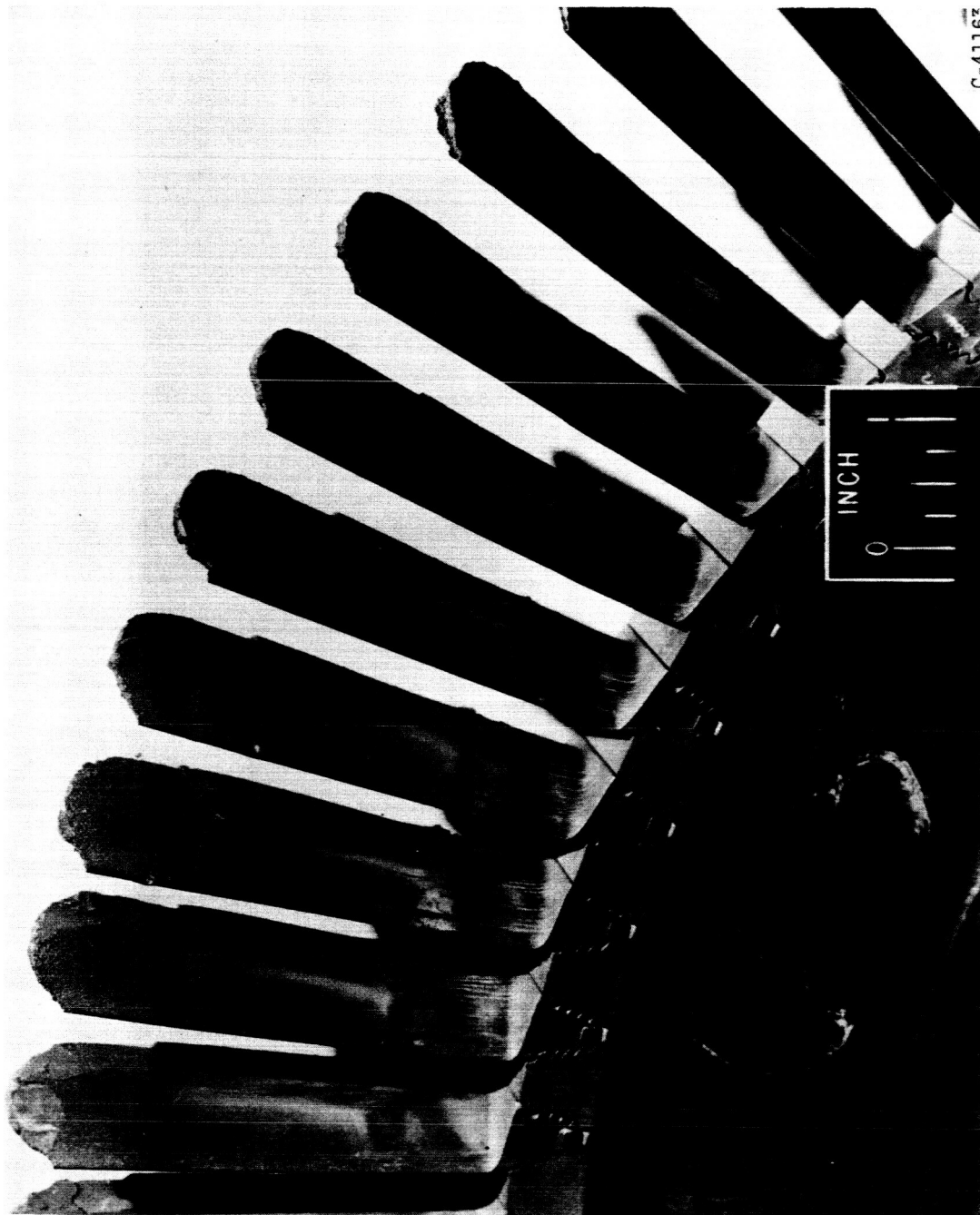
(b) Trailing edge of first-stage stator.

Figure 11. - Continued. Damaged turbine blades.



(c) Leading edge of first-stage rotor.

Figure 11. - Continued. Damaged turbine blades.



(d) Trailing edge of second-stage rotor.

Figure 11. - Continued. Damaged turbine blades.



(e) Trailing edge of second-stage stator.

Figure 11. - Concluded. Damaged turbine blades.

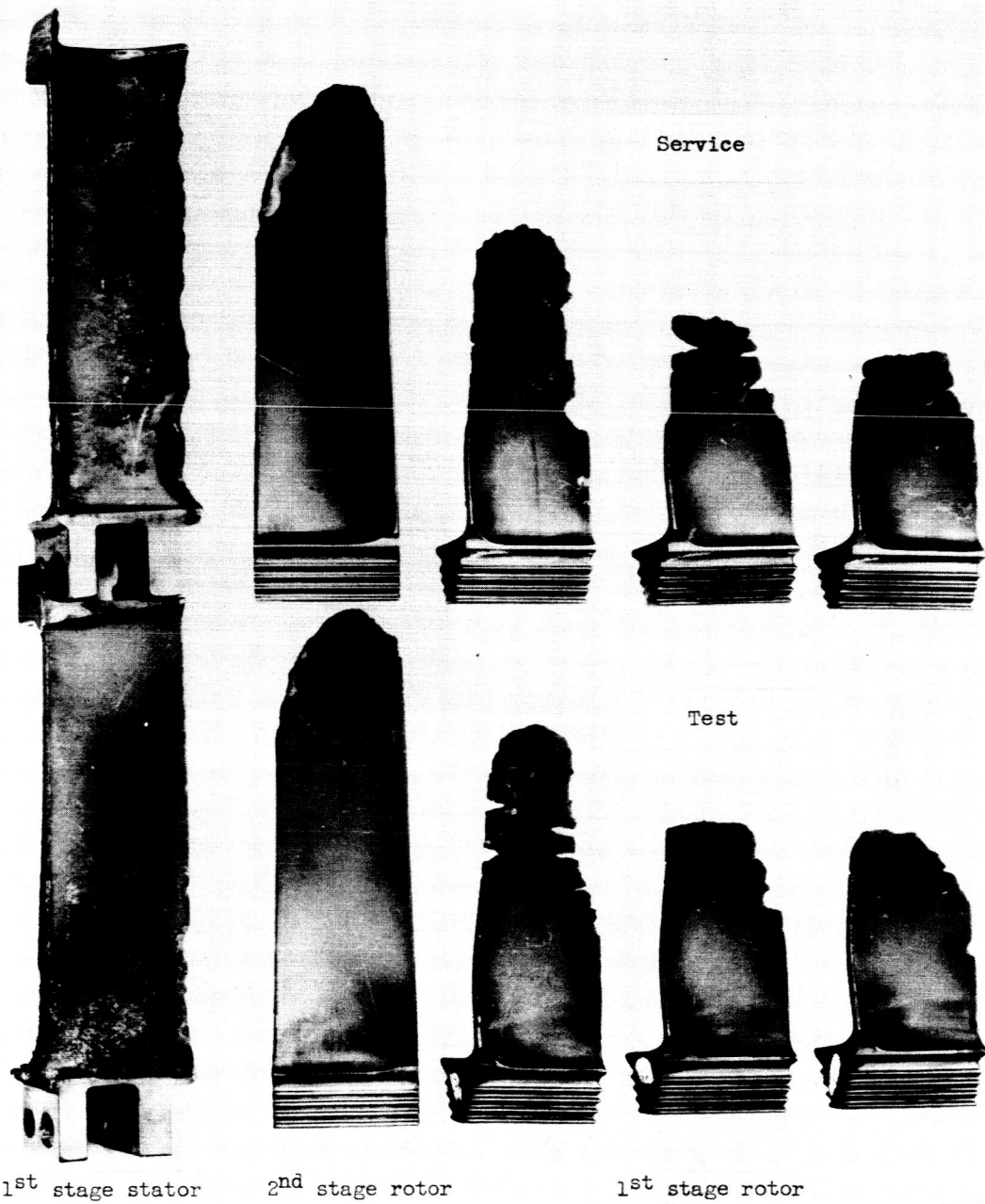


Figure 12. - Typical stator and rotor blades from test failure and service failure.

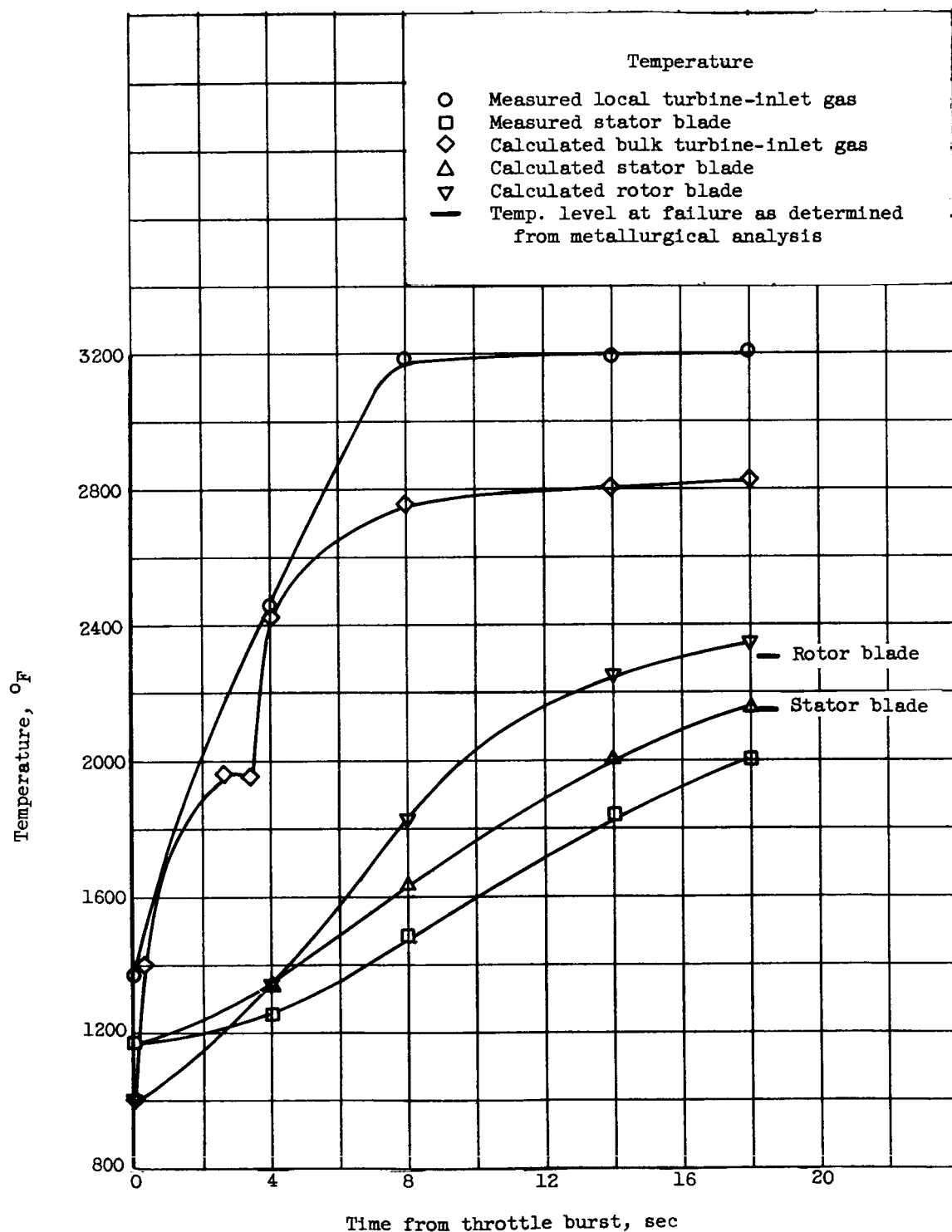


Figure 13. - Variation of gas and blade temperatures during failure run.

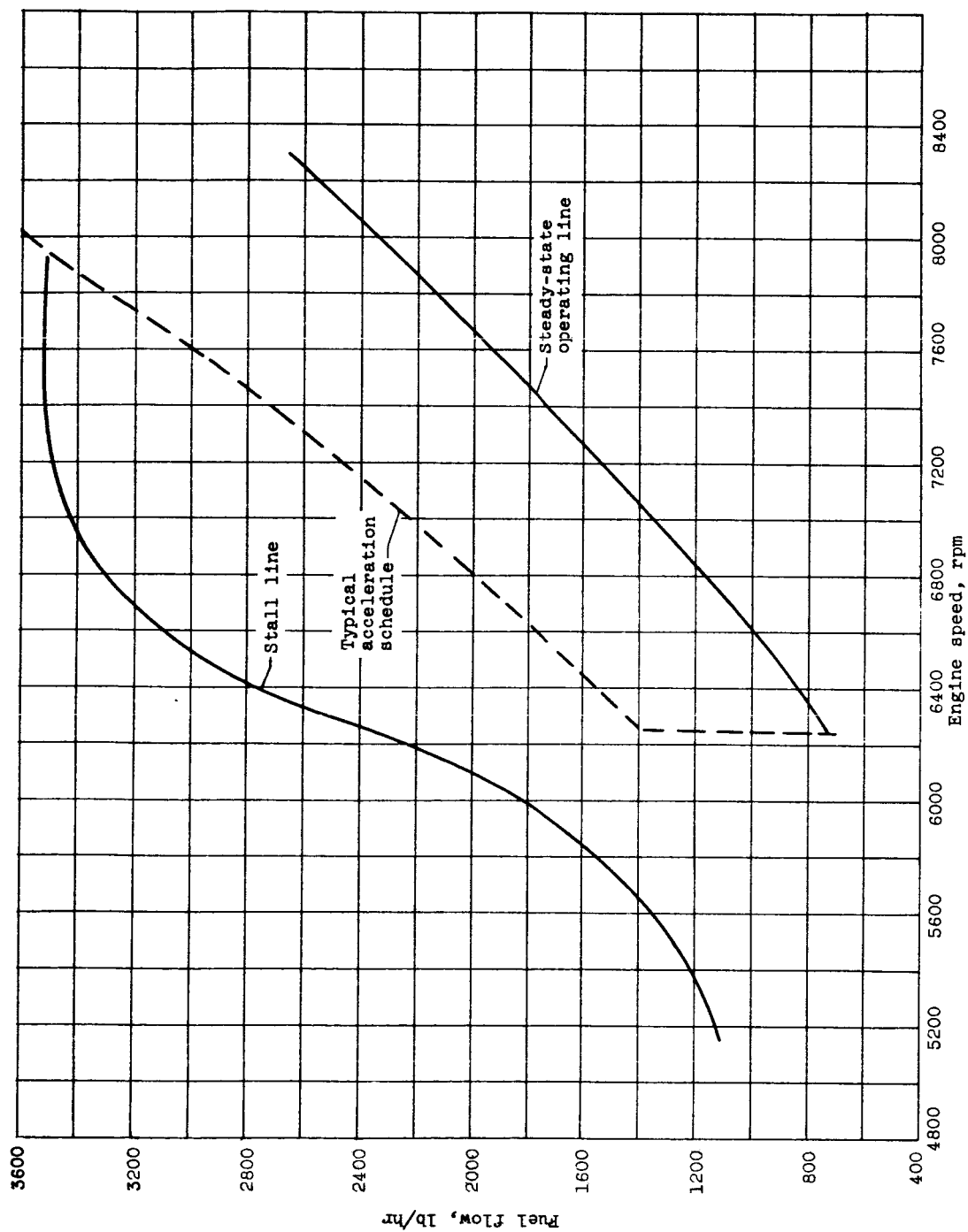


Figure 14. - Steady-state operating line, acceleration schedule, and stall line. Altitude, 35,000 feet; flight Mach number, 0.54; inlet-air temperature, -400 F.

TURBINE FAILURE INVESTIGATION OF J65-W-4 TURBOJET
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